Possible influence of the Antarctic Oscillation on tropical cyclone activity in the western North Pacific

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[1] The present study investigates how large-scale atmospheric circulation in the Southern Hemisphere (SH) modulates tropical cyclone (TC) activity in the western North Pacific (WNP) during a typhoon season (July, August, and September; boreal summer). The variation of the SH circulation of interest is the Antarctic Oscillation (AAO). In the positive phase of AAO relative to its negative phase, two anomalous highs develop over the western Pacific in both hemispheres: a huge anticyclone in southeastern Australia and a relatively weak anticyclone in the East China Sea. These teleconnection patterns are examined and compared with previous analyses. Related to the AAO variations, a statistically significant alteration of TC activities is found over the WNP. The difference in the mean TC passage numbers over the East China Sea (120°–140°E, 20°–40°N) between the eight highest-AAO years and the eight lowest-AAO years is as large as 2, equivalent to a 50–100% increase from the climatology. This change is primarily a result of more TCs forming over the eastern Philippine Sea. On the other hand, TC passage numbers slightly decrease over the South China Sea. These changes in TC activity are predominant in August and are consistent with changes in low-level vorticity over the subtropical WNP. The influence of SH circulation variability on large-scale environments and tropical convection in the subtropical NH suggest a possible usage of AAO variation for long-range forecasting of TC activity over the WNP.


1. Introduction

[2] Since the pioneering work of Thompson and Wallace [1998] on the Arctic Oscillation (AO) in the Northern Hemisphere (NH), many AO studies have been carried out to investigate its relevant impact on climate, particularly over the midlatitudes [e.g., Thompson et al., 2000; Thompson and Wallace, 2001; Gong and Ho, 2003]. The AO is represented by the leading empirical orthogonal function (EOF) mode for sea level pressure (SLP) in the region from 20°N to 90°N. This mode depicts a zonally symmetric structure of alternating positive and negative phases between the high-latitude and middle-latitude regions.

[3] Analogous to the AO, there is a large-scale swinging of SLP between polar and midlatitude regions in the Southern Hemisphere (SH). This huge atmospheric mass exchange in the SH is referred to as the Antarctic Oscillation (AAO) or High-Latitude Mode [Karoly, 1990; Gong and Wang, 1999; Thompson and Wallace, 2000]. The AAO index is defined as the time series of the leading EOF mode for SLP or 850 hPa geopotential height in the region from 20°S to 90°S. It can also be obtained from the difference in zonal mean SLP between 40°S and 65°S [Gong and Wang, 1999]. The AAO may be one of the important climate modulators in the SH, similar to the AO that influences the overall climate from the surface to the lower stratosphere in the NH. In comparison to the AO, however, the existence of the AAO has only recently become a focus of attention. Thus its influences on overall climate have not been well documented yet.

[4] In the positive phase of the AAO, the subtropical highs develop more strongly and the subpolar lows develop deeper in the SH [Gong and Wang, 1999; Thompson and Wallace, 2000; Kwok and Comiso, 2002]. The geographical distribution of the positive AAO shows two anomalous anticyclonic circulations built up in the midlatitudes of the SH at the surface [see Gong and Wang, 1999, Figure 1]: one is in the Indian Ocean (west of Australia) and the other in the Pacific Ocean (east of Australia). These two stronger...
anomalous highs in the midlatitudes coincide with an extension of the high to the pole, with the upper tropospheric jet displaced poleward, and the polar vortex confined to the polar regions during a strong positive phase. Over the tropics, there are also some modifications in the trade wind to the north of Australia. The development of a subtropical high in the Pacific Ocean in the SH invokes a strengthening of cross-equatorial flow in the western equatorial Pacific. In addition, changes in the trade wind may lead to changes in the Intertropical Convergence Zone (ITCZ) and further influence on large-scale circulation and tropical cyclone (TC) activity over the western North Pacific (WNP). These schematic diagrams are illustrated in Figure 1. Note that AAO variations in the SH and TC activities in the NH are strongest during the boreal summer and fall (austral winter and spring). This has motivated the present study.

TC activities depend on many thermodynamic (e.g., sea surface temperature (SST), atmospheric stability, midtropospheric moisture) and dynamic parameters (e.g., low-level vorticity, vertical wind shear, upper tropospheric momentum flux convergence) (Gray [1979], Frank [1987], and many others). In general, thermodynamic parameters are closely linked with each other; the atmosphere overlying high SSTs tends to be humid in the tropics, and humid air with high atmospheric temperature is apt to become unstable. During the boreal summer, the thermodynamic factors for TC genesis in the WNP are most often satisfied. Also, dynamic parameters give rise to favorable environments for the generation of TCs over the region: these include positive low-level vorticity related to the formation of the monsoon trough and weak vertical wind shear [McBride, 1995]. If there are changes in the large-scale circulation in the WNP, the dynamic parameters may be modified. These modifications may, in turn, alter TC activity.

In this study, we present evidence of a relationship between TC activity in the WNP and the AAO variations during boreal summer (July, August, and September), based on analyses of AAO index, moisture flux, some dynamic fields, and TC data. The influences of El Niño and La Niña on TC activity are also discussed.

The data used in the present study are described in section 2. In section 3, the AAO index is defined and its effects on atmospheric circulation in the SH and NH are examined along with previous studies. Further influences of AAO on TC activity and large-scale environments over the WNP are investigated in section 4. The paper is summarized in section 5.

2. Data

The information about TC activity is obtained from the best track archives of the Regional Specialized Meteorological Centers-Tokyo Typhoon Center. The data sets consist of names, longitude and latitude positions, minimum surface pressures, and maximum wind speeds of TCs every 6 hours. TCs are generally divided into three stages depending on their maximum sustained wind speed: tropical depression, tropical storm, and typhoon. In the present study, TCs refer to both tropical storms and typhoons after they get a name. So, analyzed TCs have maximum sustained wind speeds greater than 17 m s⁻¹ during their lifetime.

We also use the SLP, horizontal wind, and specific humidity data reanalyzed by the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP-NCAR) [Kalnay et al., 1996; Kistler et al., 2001]. The NCEP-NCAR reanalysis data have a horizontal resolution of 2.5° × 2.5° latitude-longitude and are available for the period 1949 to the present.

While the TC data are accessible for the period 1950 to the present, there may be some problems on the reliability of typhoon data in the 1950s and early 1960s prior to the weather satellite era. The NCEP-NCAR reanalysis data are also affected by two major changes in the observing system, upper air networks and satellite observations [Kistler et al., 2001]. To avoid the possible impact of variable data reliability on the present results, all calculations are confined to the period 1965–2002 (38 years) during which weather satellites have operated.

About 60% of the annual numbers of TCs develop in the WNP during July, August, and September [e.g., Chia and Ropelewski, 2002]. Also, most of the damage caused by typhoons in East Asia, particularly in southeast China, Taiwan, Korea, and Japan, occur during these months. Thus the present study uses 3-month data sets and these months are defined as the boreal summer.

3. AAO Index and Large-Scale Teleconnection Patterns

Prior to investigating a connection between the AAO and TC activity in the WNP, we examine the variation of the AAO and its large-scale influences in the SH and NH in this section.

3.1. AAO Index

Figure 2 shows the time series of the leading EOF mode of monthly SLP in the SH (20°S–90°S) for the entire

Figure 1. Schematic illustration of atmospheric changes during the positive phase of the AAO.
analysis period. These are equivalent to the AAO index. Although not shown in this study, the spatial distribution of the leading mode depicts a zonally elongated north-south dipole structure over the Pacific, Indian, and Atlantic Oceans, from the sub tropics to the polar regions in the SH [Gong and Wang, 1999; Kwok and Comiso, 2002]. The time series indicates that the AAO index contains strong interannual and long-term trends (Figure 2a). It also indicates that almost no correlation exists between months even in the same year.

In the present study, the AAO index is determined by the time series of the leading principal component of the monthly mean SLP in the SH. Alternatively, the AAO index can be taken from the leading EOF mode of 850 hPa geopotential height [Thompson and Wallace, 2000] and the difference in the normalized zonal mean SLP between 40°S and 65°S [Gong and Wang, 1999]. These three AAO indices are nearly identical; their correlation coefficients are larger than 0.95. Thus usage of the three different AAO indices does not have an effect on the present results at all.

Long-term variations in the AAO index might be contaminated or artificially produced because of changes in the NCEP-NCAR reanalysis. See Kistler et al. [2001] for further information regarding these changes. Marshall [2003] suggests that a trend toward the positive phase of the AAO shown in the NCEP-NCAR reanalysis could be exaggerated by a factor of 2 or 3 because of spurious negative trends in SH high-latitude pressure. Because of this, we decided to subtract the linear trend of the time series (Figure 2b) and mainly emphasize the interannual variability of the AAO. In the following analyses, these detrended time series are utilized as the AAO index.

The present study examines the relation between the AAO and TC activity by subtracting composite maps for high-AAO periods and low-AAO periods. Many previous studies have documented the fact that TC activities are greatly influenced by variations in the SST of the equatorial central-eastern Pacific, i.e., El Niño and La Niña [e.g., Chen et al., 1998; Chan, 2000; Wang and Chan, 2002]. Accordingly, we first select El Niño (La Niña) periods when Niño 3.4 SST (SST anomalies averaged over 120°W–170°W, 5°S–5°N) is greater (smaller) than +0.5 (−0.5)°C (Table 1). The selected years are always qualified for the given criteria during the three boreal summer months. There are 7 El Niño and La Niña years, respectively, in the entire 38 years. Secondly, as seen in Table 1, we choose the eight highest-AAO years and the eight lowest-AAO years, respectively, for each month among the remaining 24 years. So two thirds of the whole data sets, except for El Niño or La Niña years (total 14 years), were chosen for the analysis.
Table 1. List of High-AAO, Low-AAO, El Niño, and La Niña

<table>
<thead>
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<th>Years</th>
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<tr>
<td>High AAO</td>
<td></td>
</tr>
<tr>
<td>Entire boreal summer</td>
<td>1969, 1985, 1993</td>
</tr>
<tr>
<td>Low AAO</td>
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*El Niño (La Niña) periods are chosen when Niño 3.4 sea surface temperature is larger (smaller) than +0.5 (−0.5)°C. High (low) AAO periods are selected when the AAO index is ranked within the eight highest (lowest) values each month from all years.

AAO periods. Comparison of El Niño and La Niña periods is also discussed.

3.2. Teleconnection Patterns in the WNP

[18] Hines and Bromwich [2002] demonstrated atmospheric teleconnection between the SH and the NH, particularly over western midlatitude Pacific areas in both hemispheres. On the basis of correlation analysis of SLP, they found that two significant positive correlation centers, over southeastern Australia and the WNP, responded to variations of SLP at 37.5°S, 142.5°E for the month of August. Interestingly, similar anomalous anticyclonic circulations are found over the two regions, which are derived from atmospheric general circulation model experiments that examined the impact of Antarctic sea ice elimination [Bromwich et al., 1998]. These two studies explained that the teleconnection arises as a result of tropical convection on an intraseasonal timescale. As documented by Hines and Bromwich [2002], the increasing SLP at 37.5°S, 142.5°E denotes an intensification of the anticyclonic circulation over Australia that leads to an enhanced easterly (trade) wind in the SH sub tropics and, further results in a strengthening of tropical convection over the equatorial western Pacific (see Figure 1). Corresponding to the intensified tropical convection, two anomalous anticyclones are built up in the subtropical western Pacific in the NH and near southeastern Australia in the SH [Kiladis and Weckmann, 1992; Wang and Xu, 1997; Kiladis and Mo, 1998].

[19] Figure 3 shows the difference in the moisture flux at 850 hPa and in the outgoing longwave radiation (OLR) between high-AAO years and low-AAO years. Arrows indicate the 850 hPa moisture flux in terms of direction and magnitude, while shaded regions show decreases in OLR. The OLR data are retrieved from the series of NOAA satellites and is available from June 1974 with a missing period between March and December 1978. Details of the OLR data can be found on the NOAA web site http://www.nesdis.noaa.gov. The difference maps shown in Figure 3 are calculated on the basis of accessible data periods only.

[20] As seen in Figure 3, through all boreal summer months, decreased OLR (within which convective activity increases) straddles in vast areas along the equator, East Asia, Australia, and the surrounding oceans. In particular, pronounced decreases of OLR over the equatorial region and East Asia may be related to enhanced moisture convergence. The moisture flux differences clearly depict two anomalous anticyclonic circulations in the SH and NH midlatitudes: a huge anticyclone to the south of Australia, especially in August and September, and a relatively small anticyclone in the East China Sea and the Philippine Sea. Note that the climatological location of the subtropical high in the SH and NH during boreal summer coincides with regions where the anomalous high develops in Figure 3 (not shown). The magnitude of changes in the 850 hPa moisture flux relative to the climatology is 20–60% to the south of Australia and 20–40% in the WNP. It indicates that the subtropical highs strengthen in both hemispheres during high-AAO years compared to low-AAO years.

[21] Overall, these changes are similar to the atmospheric responses in both hemispheres to tropical convection, as described by Hines and Bromwich [2002, Figure 6d]. In association with the formation of an anticyclonic anomaly in the SH, the easterly wind becomes stronger in the SH sub tropics and deep convection intensifies along the equatorial region.

[22] It is interesting to note that an anticyclonic circulation develops over the WNP even in the NH as a result of teleconnection associated with the AAO variations in the SH. This remote anomalous anticyclonic circulation is relatively weak in July (Figure 3a) and clearly seen in August and September (Figures 3b and 3c). This is well represented in the correlation between the AAO index and anomalous 850 hPa geopotential heights averaged over its center region of variability (20°–25°N, 150°E) [e.g., Lu, 2001; Gong and Ho, 2002]. The correlation coefficients are 0.31 in July, 0.40 in August, and 0.43 in September over 38 years. The relationship between the AAO and anomalous anticyclones in the WNP in August and September is statistically significant at the 95% confidence level (the correlation coefficient is 0.33), which is derived from the Student’s t-test. To clarify the time dependence of the teleconnection, Hines and Bromwich [2002] suggested the following two causes: (1) The climatological intraseasonal oscillation of the NH summer monsoon propagates convection in a northwesterly direction, showing maximum amplitude in August and September [Wang and Xu, 1997], and (2) teleconnection patterns have a rather longer period of memory in August.

[23] The huge anomalous anticyclone south of Australia shown in Figure 3 is a typical spatial pattern of AAO variations in the SH midlatitudes. In addition, statistically significant correlation is found between the AAO index and anomalous 850-hPa geopotential heights in the WNP. It is also found that the two anomalous anticyclones in both hemispheres are consistent within each cluster of the eight highest-AAO years and the eight lowest-AAO years (figure not shown).

[24] The difference fields in moisture fluxes at 850 hPa between high-AAO years and low-AAO years (Figure 3) are comparable to the correlation map of SLP to that at 37.5°S, 142.5°E shown by Hines and Bromwich [2002]. It is noted that the present study utilizes the leading EOF mode (i.e., AAO index) in the SH, while Hines and
Bromwich [2002] used local SLP variations to obtain teleconnection patterns of large-scale circulation in both hemispheres. The similarity may be understood in terms of variations of SLP at $37.5^\circ S$, $142.5^\circ E$ being well correlated with those of the AAO. Correlation coefficients between the two time series are 0.44 for the three boreal summer months, significant at the 99% confidence level.

4. TC Activity Associated With AAO Variations

4.1. TC Passage Number

Figure 4 shows the climatological distribution of passage number (Figure 4a) and the difference between high-AAO periods and low-AAO periods (Figure 4b) of TCs during the boreal summer within each $5^\circ \times 5^\circ$ latitude-longitude grid box. Each six-hourly TC position is binned into the corresponding $5^\circ \times 5^\circ$ grid box and the same TC entering the same grid box is counted only once. The climatological values of TC passages are defined by dividing the total number of TCs during boreal summer by 38 (38 years). Since TCs generally migrate to the western periphery of the subtropical North Pacific high, the TC passage number is higher over the South China Sea and the East China Sea (Figure 4a). Over the two regions, more than 3 TCs appear in each $5^\circ \times 5^\circ$ grid box every boreal summer. The passage number also indicates an elongated passage track (areas more than 2 TCs) extending toward Korea and Japan.

[26] Corresponding differences (the eight highest-AAO years minus the eight lowest-AAO years) of the total TC passages for high-AAO and low-AAO periods are shown in Figure 4b. The differences are divided by 8 (8 years) to represent the number of TC passage per boreal summer. On the whole, increased passage numbers dominate the analysis domain: there are 26 grids where TC passage increases, only 8 grids where TC passage decreases. However, only 8 of the grids where TC passage increase pass the significance test and none of the grids where TC passage decreases pass the test. The primary change is observed over the East China Sea, Japan, and the Philippines. The change is as large as 2 and matches a 50–100% increase from the climatology (i.e., about 3 TCs) during high-AAO periods compared to low-AAO periods. Also, most of these changes are significant at the 95% confidence level (see dotted mark inside circle). While TC passage decreases in southeastern China and increases over the east part of the

Figure 3. Composite of moisture flux difference between high-AAO years and low-AAO years at 850 hPa for the month of (a) July, (b) August, (c) September, and (d) all three months. Decreased OLR regions are shaded. Thick arrows are significant at the 90% confidence level for zonal or meridional flux. The units are $10^{-3}$ m s$^{-1}$ for moisture flux and W m$^{-2}$ OLR. Contour intervals are 10 W m$^{-2}$. 
between the two periods are comparable in July and September. However, the numbers are larger in August: 41 for high-AAO periods and 24 for low-AAO periods (Figures 5b and 5e). In August 1985, as many as 8 TCs passed the preferred local area and 3 of them struck Korea, which is influenced by 2 or 3 typhoons every year. It is interesting to note that passage numbers larger than the monthly average are frequent in high-AAO periods compared to low-AAO periods, even in July and September (5 versus 3 in July, 3 versus 0 in September).

[29] The number of TCs that have passed the preferred local area was also examined for 8 moderate or neutral AAO years each month (figure not shown). The variability is too large compared to the high and low extremes, so the relationship between the AAO and the number of TCs passing through the local area is established in its extreme phase only.

4.2. TC Genesis

[30] The changes in TC passage in the East China Sea may be due to those that occur in the location of genesis [e.g., Ho et al., 2004]. Figure 6 shows the spatial distribution of the climatology (Figure 6a) and the difference between high-AAO years and low-AAO years (Figure 6b) over the WNP. Many TCs originate from the Philippine Sea where SSTs are high and the overlying atmosphere has higher instability during the boreal summer (Figure 6a). Over the region 115°–150°E and 10°–20°N (a box in Figure 6a), about 0.5 TCs form every boreal summer within each 5° × 5° latitude-longitude grid box. Surrounding this region, fewer TCs develop. There is no region where more than 0.2 TCs appear per boreal summer north of 25°N.

[31] The differences in the frequency of TC genesis between the two periods are displayed in Figure 6b. TC genesis increases near the coast of the Philippines and east of 140°E and decreases over the South China Sea. Because many of the TCs originate from the Philippine Sea and move into the East China Sea, Korea and Japan, part of the increase in TC passages over the East China Sea and Japan may be explained by changes in the location of TC genesis. However, the areas of significant change are localized and scattered, so they cannot easily explain the changes of TC passage over the East China Sea. We then examine the actual tracks of TCs to search for the cause of changes over the East China Sea. Although the map of actual TC tracks exhibits a high degree of complexity because of the large number of TCs, we found that the increase near the coast of the Philippines makes a minor contribution to the overall changes (figure not shown). It is clear that the TCs formed over this area generally move straight northwestward and it is the increase of TC genesis east of 140°E that accounts for the major changes.

4.3. Large-Scale Environments in August

[32] An apparent increase in TC passage is found in the East China Sea in August, corresponding to AAO variations (Figures 5b versus 5e). This enhanced TC activities would primarily be caused by frequent generation of TC in the region east of 140°E. In this subsection TC generation and any relevant large-scale environments during the month of August are examined.

[33] Figure 7 presents genesis locations of TCs for the eight high-AAO years (Figure 7a) and the eight low-AAO
years (Figure 7b), respectively. Averaged over the whole WNP basin, more TCs develop during high-AAO years than low-AAO years: 59 versus 46. However, the regional features of the differences are rather diverse. The most striking differences are found in the Philippine Sea and the South China Sea. Over the Philippine Sea (120°–150°E, 5°–20°N; larger box in Figure 7), the number of genesis events is 29 for high-AAO years and 17 for low-AAO years. In particular, about 55% (16) among the total of 29 TCs for high-AAO years originated in the eastern Philippine Sea (140°–150°E, 5°–20°N; shaded box in Figure 7), but 6 TCs originated in the same area for low-AAO years. The opposite is true in the South China Sea (west of 120°E): 3 genesis events for high AAO years and 11 for low-AAO years.

Over the Philippine Sea (120°–150°E, 5°–20°N), TC genesis numbers each August are 3.6 and 2.1, respectively, during high-AAO years and low-AAO years. The climatological value of TC genesis within the domain is 2.6 except for El Niño/Southern Oscillation (ENSO) years and its interannual standard deviation is 1.2. The difference (1.5) for the two periods is significant at the 95% confidence level using the Student’s t-test.

[34] Climatologically, the eastern Philippine Sea is the most active area of TC genesis during August. About half of TCs that develop in the WNP originate in this region. It is interesting to note that the difference in TCs in the East China Sea, 17 (41 versus 24; Figures 5b and 5e), is comparable to that of TCs formed in the eastern Philippine Sea, 10 (16 versus 6; shaded box in Figure 7). To confirm this relation, all tracks of TCs formed in the eastern Philippine Sea are depicted in Figure 8 for the eight high-AAO years (Figure 8a) and the eight low-AAO years (Figure 8b). 14 TCs among 16 TCs enter the East China Sea for high-

Figure 5. Time series of tropical cyclone passage number averaged over 20°–40°N and 120°–140°E. A horizontal line indicates the mean number of tropical cyclone passages over the region.
AAO years (Figure 8a) and 2 TCs only among 6 TCs enter the East China Sea for low-AAO years (Figure 8b). Therefore it can be demonstrated that the increase of TC passage in the East China Sea for high-AAO years is mainly due to frequent genesis events in the eastern Philippine Sea during August. Furthermore, it is suggested that the relationship between AAO-tropical cyclone activities in the East China Sea can be understood as resulting from changes in thermodynamic and/or dynamic parameters over the genesis region. These are discussed in the following.

Concerning thermodynamic parameters, differences in SST and vertical thermodynamic instability, such as the vertical distribution of the equivalent potential temperature of a hypothetically saturated atmosphere, between the two periods were investigated. While figures are not shown here, SST differences are less than 0.2°C for the boreal summer in the entire WNP basin except for near continental landmasses. Corresponding vertical instability does not show any significant difference either. It is well known that the region of the WNP is covered by SSTs higher than 27°C for the whole boreal summer, and is referred to as a ‘warm pool’. Associated with high SSTs, the overlying atmosphere attains a potentially unstable condition and strong surface winds induce exchanges of heat and moisture. This means that TCs can be produced if favorable dynamic parameters, such as positive low-level relative vorticity and weaker vertical wind shear, are supplied.

[37] Concerning dynamic parameters, Figure 9 illustrates the distributions of climatology and differences (high-AAO years minus low-AAO years) in relative vorticity at 850 hPa and the vertical shear in the zonal wind at 200 and 850 hPa during August. As can be seen in Figure 9a, for the August climate, regions of positive relative vorticity are found over the South China Sea, the Philippine Sea, central China, and Korea. This positive relative vorticity may be a result of the northward movement of the ITCZ (into the South China Sea and Philippine Sea) and a development of the East Asian monsoon trough (over central China and Korea) during summer. Corresponding differences in the 850-hPa relative vorticity (Figure 9b) show substantial changes in the subtropical WNP.

[38] Jeffries and Miller [1993] documented three different mechanisms controlling the increase in low-level vorticity in the WNP: (1) an enhanced easterly trade wind due to a strengthening or equatorward movement of the subtropical ridge, (2) enhanced convection in the equatorial trough due to a cross-equatorial flow from the SH, and (3) a deepening of the monsoon depression over the Philippines and eastward advection associated with the low-level flow from the SH. As can be seen in the difference distribution of the 850-hPa moisture flux (Figure 3b), an anomalous anticyclone develops in the East China Sea and a cross-equatorial flow occurs over Indonesia. This means that the first and...

Figure 7. Spatial distribution of tropical cyclone genesis in August for (a) the eight highest-AAO years and (b) the eight lowest-AAO years.

Figure 8. Regional Specialized Meteorological Centers best tracks of all tropical cyclones originated from the eastern Philippine Sea (shaded box) in August for (a) the eight high-AAO years and (b) the eight low-AAO years. Dots are the locations of tropical cyclone formation.
second of the above three mechanisms are responsible for an increase in low-level vorticity.

The second of the above mechanism is well described by Love [1985a, 1985b] who has presented evidence that winter hemisphere cold surges result in tropical cyclone genesis in the summer hemisphere. Love [1985a] displayed several cases showing how enhanced cross-equatorial flow, drawn from a pressure rise in the winter hemisphere mid-latitudes, results in an increase in the monsoon westerlies in the summer hemisphere.

The climatological vertical zonal wind shear in August is shown in Figure 9c. It is generally agreed that the most active region of TC genesis is located in a weak shear zone [Gray, 1968; Elsberry and Jeffries, 1996; Bracken and Bosart, 2000]. Over a region of near zero wind shear, environmental flow does not rip the vertical structure of the TC so that latent heat generated by convection is not ventilated with its environment, aiding in development. The differences in vertical wind shear (Figure 9d) indicate a weak decrease in the absolute magnitude of vertical wind shear over the Philippine Sea, though not statistically significant, which are consistent with an increase in tropical convection and 850-hPa relative vorticity.

To investigate the source of the differences, the wind fields at low levels and aloft are examined separately (figures not shown). The increase in differences over the Philippine Sea is mainly due to the weakening of the monsoon westerlies caused by low-level easterlies. On the other hand, the major differences located around the dateline result from the strong upper level anomalous anticyclone.

4.4. Impact of ENSO on TC Activity

Although it is not within the main scope of the present study, the influence of ENSO on the TC activity in the WNP is briefly discussed in this subsection. In association with the changes in SST in the central and eastern tropical Pacific, large-scale circulations, e.g., the Walker Circulation, local Hadley Circulation, and the East Asian jet stream, are modified. In particular, it is well known that the Walker Circulation shifts to the east during El Niño episodes [Chan, 1985]. Also, in response to changes in large-scale circulations, crucial factors that influence TC activity such as vertical wind shear and thermodynamic instability may be changed.

Many previous studies have described the influence of ENSO on TC activity in the WNP. During ENSO years,
in particular, the major location of TC genesis shifts eastward in association with changing tropical SSTs. Therefore, the predicted ENSO information can be used to give long-range forecasts of TC activity in some Pacific countries. However, its influences on East Asian countries such as Korea and Japan are known to be, at best, moderate.

[44] Figure 10 shows the difference in the frequency of TC passages (Figure 10a) and of TC geneses (Figure 10b) between seven El Niño years and seven La Niña years (see Table 1 for detailed information on those years). The difference in the number of passages (El Niño minus La Niña) indicates that the number of TC occurrences increases by up to 2.5 in the eastern half of the domain (east of 135°E) as seen in Figure 10a. Such large changes correspond to a 100% increase above the climatology in the maximum region (Figure 10a versus Figure 4b). While the number of passages decreases to the south of Korea and Japan and increases in the South China Sea, their significance is not great.

[45] Most of the changes in the number of passages associated with ENSO can be explained by the eastward shift of the location of genesis (Figure 10b). The relation between ENSO and the location of genesis has been examined in many studies [Chen et al., 1998; Chan, 2000; Chia and Ropelewski, 2002; Wang and Chan, 2002]. Wang and Chan [2002] demonstrated that low-level shear vorticity is generated in the southeast quadrant of the northwestern Pacific during El Niño and it leads to enhanced TC genesis. On the other hand, upper level convergence induced by the deepening of the East Asian trough and strengthening of the subtropical northwestern Pacific high suppressed TC generation over the northwest quadrant at the same time.

5. Concluding Remarks

[46] This study examines the influences of the AAO, an extensive mass exchange between the SH midlatitudes and Antarctic regions, on large-scale circulations and tropical cyclone activity in the NH, particularly the subtropical WNP. The difference between two composites of the highest eight AAO years and the lowest eight AAO years shows an apparent teleconnection pattern in the western Pacific in both hemispheres: a huge anticyclone to the southeast of Australia and a relatively small anticyclone in the East China Sea. The formation of the anomalous anticyclone in the East China Sea results from enhanced tropical convection associated with a northward propagation of climatological intraseasonal oscillation [Wang and Xu, 1997]. This teleconnection pattern is more evident in August than in July and September and is associated with enhanced tropical convection phase-locked to a northward propagation of climatological intraseasonal oscillation [Hines and Bromwich, 2002].

[47] The number of TC passages increases in the East China Sea and Japan (120°–140°E, 20°–40°N) during high-AAO periods compared to low-AAO periods. In some grid boxes of 5° × 5° latitude-longitude size, the passage differences (high-AAO periods minus low-AAO periods) correspond to 50–100% compared to climatology. Averaged over the whole preferred region, differences between the two periods are 0.9 while climatological TC passage values are 3 for the boreal summer months. Consistent with the time-dependent characteristics of the teleconnection pattern, changes in TC activity are also most dominant in August. Most TC passages in the East China Sea and Japan are due to more frequent TC genesis in the eastern Philippine Sea where 16 (6) TCs develop for high (low) AAO periods. An increase in low-level relative vorticity is mainly responsible for providing favorable environments for TC generation over the region.

[48] The influence of ENSO on TC activity is also discussed. By comparing the influence of the AAO and ENSO on the number of TC passages (Figure 4b versus Figure 10a) and geneses (Figure 6b versus Figure 10b), it is found that their influences are comparable. Particularly, while the impact of ENSO on the number of passages over the East China Sea and East Asia is negligible, that of AAO is noteworthy. However, the influenced areas by ENSO are much larger.

[49] In summary, our observations reveal that AAOs have a significant influence on large-scale circulations and TC genesis in the WNP. Some thoughts regarding the dynamics/physics of the AAO-TC relation are discussed on the basis of existing findings and knowledge which is still rather primitive. Current global models cannot predict the phase of the AAO with a lead of several months. Moreover, the AAO index represents a strong month-to-month variability even within the same summer. Thus the AAO-TC relation...
observed in this study may not be used for forecasting seasonal activity of TCs at the present time. Nevertheless, this teleconnection signal will be helpful in predicting TC activity over East Asia in the future.

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References


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